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# Operation of Digital Systems in Severe Electromagnetic Environments

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## Naval Undersea Warfare Center Detachment
New London, Connecticut



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# PREFACE

This document was prepared as a project to fulfill the requirement of a Master of Science Degree in Engineering at the Hartford Graduate Center.

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# EXECUTIVE SUMMARY

New digital communication between units is desired in the modernization of a system. Two units of an existing system are linked by circuitry that supplies direct current power, and the connecting wires have been selected for conversion to digital use. This wiring is located within a large bank of alternating current power cables and runs parallel to these cables for several hundred feet. The direct current system realizes no interference from this physical configuration, however, the power wiring radiates electromagnetic fields sufficient to couple noise voltage into a digital system.

This project quantifies the effects of high levels of low frequency electromagnetic fields on standard digital communications wiring so that a sufficiently immune circuit configuration can be selected for any application.

A model of the expected electromagnetic environment is presented and wire termination voltage measurements are made under varying field and impedance conditions. Standard digital communication design is then examined for compatibility with this environment.

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# PART 1

## INTRODUCTION

Increasingly, society is using digital communication; the transfer of digitally encoded information from one electronic unit to another. This is often accomplished by microprocessor and line driver circuitry and through use of fiber optics, coaxial cable and twisted pair wire. Also, greater electronic system populations on fixed-size platforms, such as buildings and transport, are creating denser power environments. This forces power supply and digital communication cabling into close proximity, and digital immunity to noise sources must be ensured.

The expensive and intrusive nature of creating paths for cable or optics on an existing platform requires that digital communication be accomplished utilizing existing cables. On one project, the twisted wire pairs made available through a specification are currently unused, intended for direct current, and embedded in a main power cable bank.

An analysis of cable spacing guidelines (Reference 1) reveals that ordinary digital communications between system units would be likely to fail with this configuration. This failure mode is caused by the digital cable existing at zero spacing with alternating current power cables and running for long lengths relative to separation distances.

Figure 1 shows a possible cross section of a twisted wire pair experiencing a severe low frequency electromagnetic environment.

Resolution of the unexpected ramification in the requirement (an extremely high operational ambient electromagnetic field for a digital cable) is critical. It is not advisable to violate the spacing guidelines; however, provision is made for special cases. As a special case, the system must be operational at all times and not affect the platform.

This project addresses the system immunity portion of this case. It establishes values for a maximum mean magnetic field and electrically coupled voltage to be experienced by conductors within a digital cable. The modeling is then extended to establish an expected maximum noise voltage at the communication circuitry.

To evaluate the effective fields necessary to disrupt communication circuitry, a three meter length of twisted pair wiring is subjected to electromagnetic fields ranging from an ambient level up to the estimated maximum. The resulting voltages at the wire terminals are measured under different impedance and are tabulated and graphed. Some of the analyzer outputs are included as figures in the results section.

The electromagnetic fields are created with a modified Helmholtz type coil; the coil current is monitored with a current probe. Voltage measurements are obtained through direct connection to a "Fast Fourier Transform" type signal analyzer, with calibration via a magnetic loop antenna. This method is very accurate and also provides a measure of harmonic content.

Finally, to provide recommendations for digital communication in severe low frequency electromagnetic field environments, standard circuit immunity values are compared to these results.

The data is found to be approximately linear over a logarithmic scale; extrapolation of this data is included and should be useful over a wide range of applications.

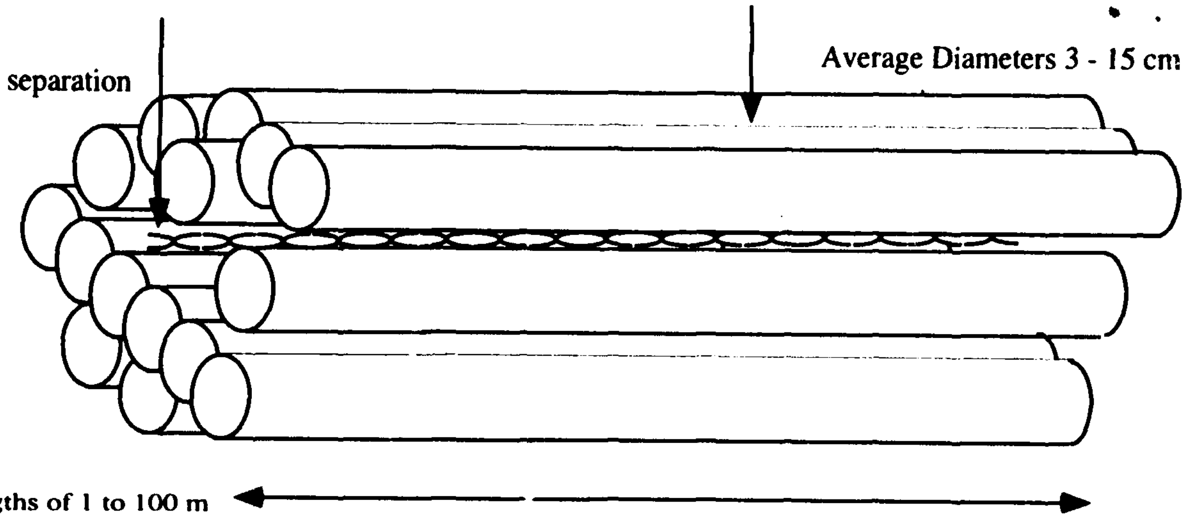



Figure 1.1 - Cable Bank Cross Section

# PART 2
# THEORY AND MODELING

## Radiated Electromagnetic Field Environment

The maximum energy in power systems is generally present at 60 hertz, 400 hertz and their associated harmonics. Voltage potential, current flow, proximity, and geometry define the severity of a power system electromagnetic environment. Magnetic field radiation results from current flow and electric field radiation is caused by voltage potential difference.

## Power Cable Radiation

The maximum electric fields from a collection of power cables will be proportional to the maximum voltage drop present in that group of cables. A nominal maximum of 132 volts is used in a capacitive circuit model to determine voltage induced on a parallel conductor.

The maximum magnetic field is not as simple to estimate. A composite magnetic field at the surface of a conductor can be created analytically by surrounding the subject cable with cables carrying an estimated maximum current. This layering of cables desists when falloff effects make the induced field comparable to the earth's field, or when unreasonable dimensions are reached. Figure 2.1 illustrates this for the example of a 6 cm diameter power cable and a 1 cm diameter signal cable. To achieve a worst case, these dimensions are typical for 300 ampere maximum service radiators and for 18 gauge twisted pair wire.

Also to achieve worst case conditions, the length of the cables is considered very large relative to their separation from the digital cable. Accordingly, the scalar electromagnetic field from a power cable at each distance (r) is calculated using the Biot-Savart law for a straight current (I) carrying filament of infinite length (Reference 2):

(1) $H = I / r$ amperes per meter

and, assuming free space permeability in henrys per meter, the scalar flux density B is:

(2) $B = u_0 H$ tesla.

Substituting (1) into (2) and using $10^4$ gauss per tesla:

(3) $B = 10^4 I u_0 / r$ gauss.

The flux density at any frequency f in hertz is given by (Reference 3):

(4) $B(f) = B * (1/f)^n$ gauss,

where f=60 Hertz and n=1 (linear falloff) are typical values. A general equation for electromagnetic flux density in gauss at close metric distances to a long current carrying cable in free space is then:

(5) $B = 10^4 \, I \, u_0 / (f \, r)$ gauss.

Table I contains the calculations for B(f) from 6 centimeter diameter, 300 ampere, 60 Hertz power cables at each of the six distances (i.e. B1= 10,000 (g/T) * 300 A * 1.25e-6 H/m / 60 Hz *.035m = 1.78 g).

Table I - Estimated Magnetic Flux Densities

| B(f) | cable | separation |
|---|---|---|
| (gauss) | (#) | (m) |
| 1.78 | 1 | .035 |
| 0.84 | 2 | .074 |
| 0.64 | 3 | .097 |
| 0.47 | 4 | .132 |
| 0.43 | 5 | .146 |
| 0.36 | 6 | .162 |

Each field at a distance is then multiplied by the number of cables at that distance. All fields are then summed to form a resultant worst case field at the signal cable. This is reasonable because the permeability of aluminum, steel, copper and insulation are so low at 60 hertz, blockage by ordinary cables is negligible. Also, phase and frequency correlation of radiators is likely if they are connected to the same generator.

A general form for estimating the electromagnetic flux density at the surface of a cable surrounded closely by long high current carrying cables is then:

(6) $B_{resultant} = \Sigma \; k_n * B_n$ n == distance that has at least one radiator

where $B_n$ is the flux density due to a radiator at a single distance and the $k_n$'s are a "packing factor" equal to the number of radiators present at that distance. The number of distances at which there is at least one radiator is generally limited by field attenuation, but like k, can be determined by geometry.

In the geometry of Figure 2.1, the Earth's field (~.3g) is comparable to the radiation at distance six and dimensions are sizable. A reasonable estimate for the maximum likely steady state electromagnetic flux density at the digital signal cable is then:

(7) $B_{resultant} = 3*B_1 + 3*B_2 + 6*B_3 + 6*B_4 + 3*B_5 + 6*B_6 =$ 17.97 gauss.

Because they are representative cables with constant current this is a mean value; real situations would also be affected by cyclic highs and lows in power consumption and recurrent transient power needs.

## Digital Cable Susceptibility

Susceptibility, the ability of a twisted pair wire to be affected by its electromagnetic environment, depends on proximity to a source or sources, construction, and the terminal impedance. Standard configurations an l typical dimensions are used in the models estimating the voltages.

### Voltages at Wire Terminals in a Low Frequency Electromagnetic Field

The voltage on the digital conductor will be the sum of the voltage induced by the magnetic field and the voltage capacitor coupled through the electric field. A digital communication circuit will have some sensitivity to a noise voltage at its connection to the wire used for communication. Voltage induced onto conductor pairs by a maximum continuous field and an expected value at wire termination is calculated to be 4.483 volts, a non-trivial noise immunity value.

## Magnetic Field Induction of Voltage onto Wire Pairs

It is known that wiring loops create surface areas for electromagnetic field induction into unwanted current flow, and that these surface sizes are dependent on physical configuration. Furthermore, the voltage induced onto a wire loop is proportional to the time varying flux orthogonal to that surface and is given by Faraday's law:

(7) $V = -d\Phi/dt$ volts (webers/s)

where flux is defined as the surface integral of the flux density vector:

(8) $\Phi = \int_S \mathbf{B}\, d\mathbf{S}$ webers.

Using an orthogonal loop geometry in (8) and a sine function in (7) and substituting:

(9) $V = B\,A\,f$ webers/s (volts)

where A is in square meters f is in hertz and B is webers per square meter.

Elliptical Surface Area Model. Each twist of a pair appears as a loop to the electromagnetic flux and cancels, and an simple elliptical model for the remaining odd twisted pair wire loop area is:

(10) $A = \pi\,(S/2)\,(L/N)/2$

where S is the separation between the wires in meters, L is length of the cable in meters and N is number of twists. Figure 2.2 depicts this model. A more physically accurate, but not significant numerically, model is given by helical geometry and Bessel functions. (Reference 4).

The voltage induced on a twisted pair wire at a single frequency is given by substituting (10) into (9):

(11) $V = B\,f\,[\pi\,(S/2)\,(L/N)/2]$ volts.

Using the result for B derived in the previous section, and typical values for 5 meters of 18 gauge 100 twist per meter wire pairs:

(12) $V = (17.67 * 60)[\pi\,(.01/2) * (5/500)/2] =$ 0.083 volts.

This shows that although large magnetic fields are created when high current levels are present on conductors, the surface area of a standard twisted pair is sufficient to reject most magnetic field generated noise voltage.

Coupling of Electric Fields onto Conductors

The voltages used in power transmission can create sufficient electric fields to capacitor couple voltage onto parallel conductors. A number of conductors at high voltage in close proximity to a digital cable for lengths of several meters will be considered.

Transmission Line Model. Parameters have been derived (Reference 5) that describe the capacitance between two wire lines at low frequencies in homogeneous dielectric. The capacitance per unit length between two conductors of radius a and separated in space by distance d is:

(13) $C = \pi \varepsilon / \ln (d/a)$

where $\varepsilon$ is the permittivity of the space between the conductors

For a standard conductor of a twisted pair positioned on a power cable, the radius will be approximately a tenth of a centimeter and the distance will equal the thickness of both insulation layers. The permittivity of a 2 centimeter thickness of polyethylene insulation $2.0 \times 10^{-11}$ farads per meter. The capacitance is then given by:

$C = 3.14 * 2.0 \times 10^{-11} / \ln (0.005/0.001) = \underline{39 \times 10}^{-12}$ farads/meter.

The voltage drop over the length of cable will depend on the inductance per foot of the conductor and any other loading. The total coil length of 48 meters and the total coil inductance is 100 mH; the inductance per meter is 2.08 mH/m. At a maximum of 132 volts applied, the maximum voltage per meter is 2.75 V/m. This results in eight 8.2 volt conductors parallel to the digital conductor as in Figure 2.3.

Capacitive Circuit Model. The voltage induced by electric fields will be modeled as a lumped stray capacitance between single conductors. Consequently, the voltage expected at the wire circuit can be modeled and derived by a circuit model as in Figure 2.4. The resulting maximum worst case voltage is 4.4 Volts.

Voltage Between Conductor and Shield

If the a single wire and shield are perfectly coaxial, the fields cancel and the expected voltage is zero. However, the twisted pair conductor is positioned unevenly around the shield axis and the fields and resulting voltages are non-zero. Voltages that appear represent the percent imbalance in the wire twists.

## Immunity of Circuitry

The result derived above is an open circuit voltage; the input/output impedance of the communication terminals of the integrated circuits will determine how much voltage appears at the circuitry. The connection of the shield in a 360 degree manner to the casing of the circuitry will provide immunity to the electric fields; transient effects should also be taken into consideration.

Digital Receiver Noise Margins

The driver output voltage is generally greater than or equivalent to receiver circuit input sensitivity and their operational combination with any hysteresis will determine the voltage necessary to disrupt communication (Reference 6).

Logic Gates. It is possible to communicate digitally over a short distance by directly connecting logic gates. Standard TTL gates have a noise margin of .4 volts and would be absolutely corrupted in a severe electromagnetic field environment.

Schmitt triggers. These can be used as receivers and have a higher sensitivity of 1.1 volts, but still would not survive in this environment.

Single Ended Receivers with Hysteresis. In combination with certain drivers that have wide output voltage swings, receiver sensitivity can be made as great as 9.1 volts. However since this is twisted pair wire, not coaxial cable, the circuitry could be subject to common mode electromagnetic interference. Since single ended communications lends itself to serial communication, capacitance may also limit the speed of the operation.

Balanced Line Receivers with Hysteresis. Dual supply differential line receivers have high common mode rejection, high input impedance and work well with the uniformity and low impedance of twisted pair wires. In combination with a balanced collector output voltage driver noise margins of 10 volts are readily obtainable. It is possible to increase collector voltages and obtain 30 volt noise margins.

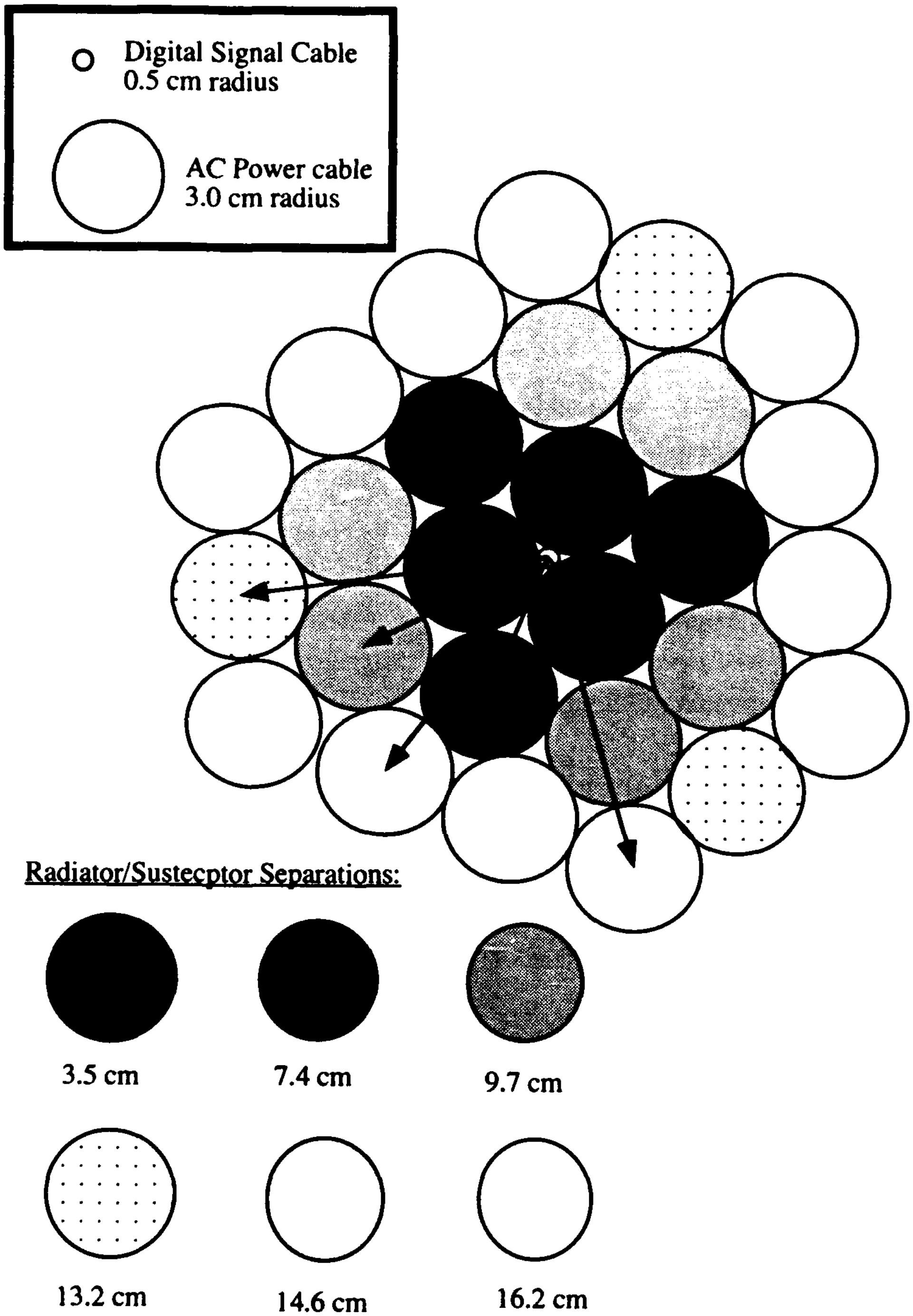
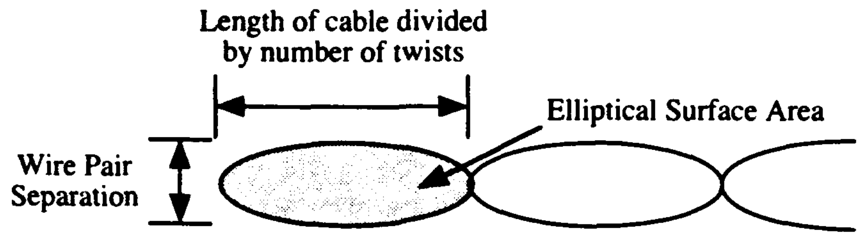
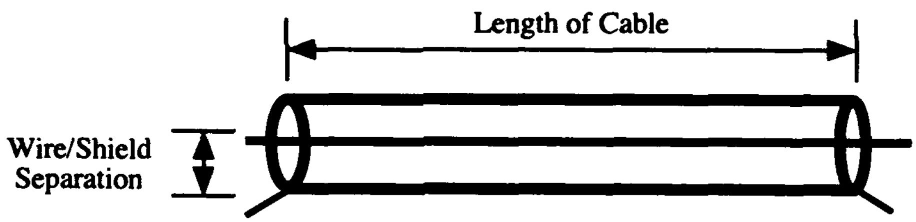



Figure 2.1 - Composite Magnetic Field Model



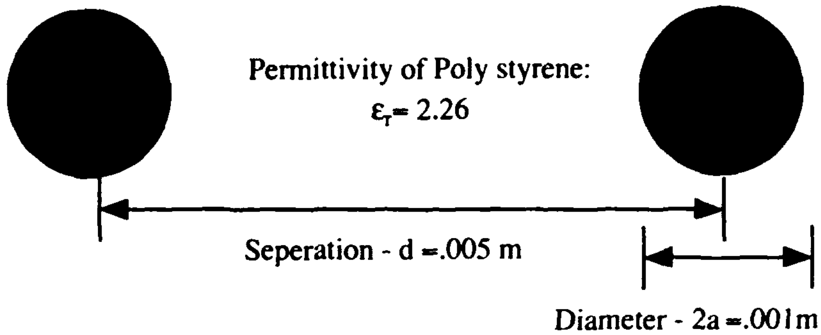

Fields increase linearly with surface area




Wire and Shield - Coaxial Model for Surface Area

Fields are identically zero

Figure 2.2 - Twisted and Coaxial Wire Pair Models




Derived form for capacitance between two parallel conductors in a homogeneous medium:

$C = \pi\, \varepsilon / \ln (d/a)$ farads per meter.

Permittivity definintion:

$\varepsilon = \varepsilon_0 \varepsilon_r$ $\varepsilon_0 = 8.854 \times 10^{-12}$ f/m in free space

$C = 6.28 \times 10^{-11} / \ln (.005/.001)$

<u>$C = 39$ pF/m</u>

132 Volts Maximum Applied

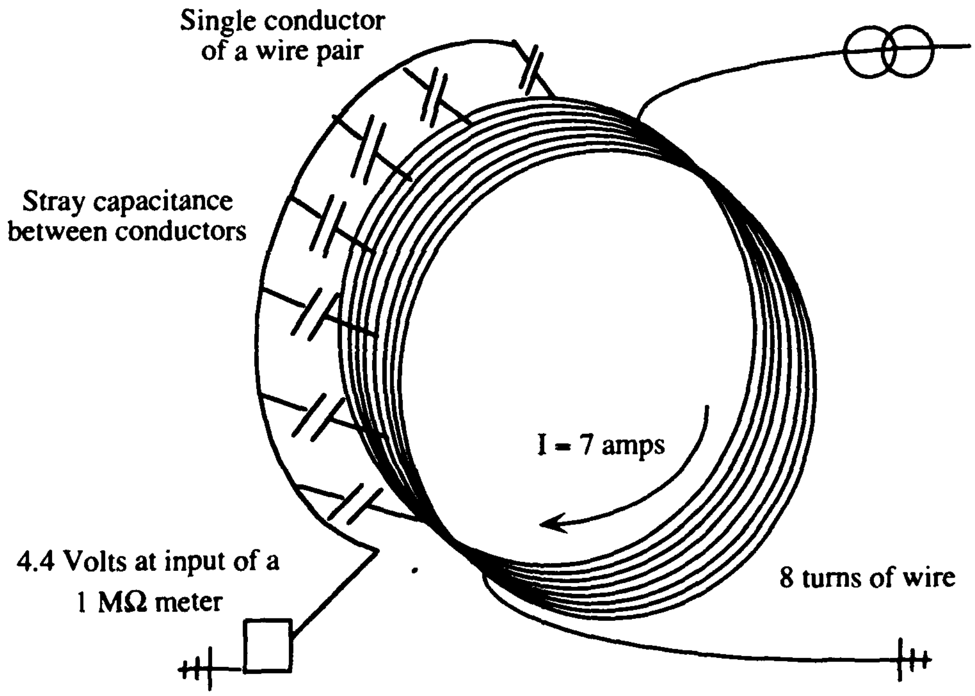
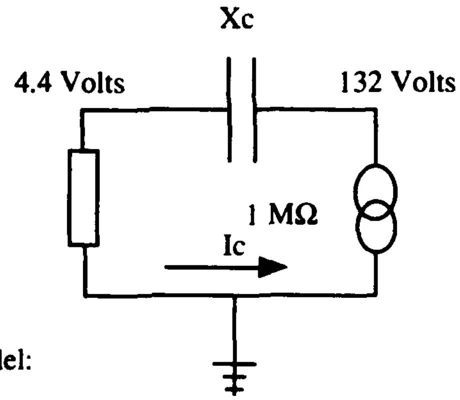



Figure 2.3 - Transmission Line Model

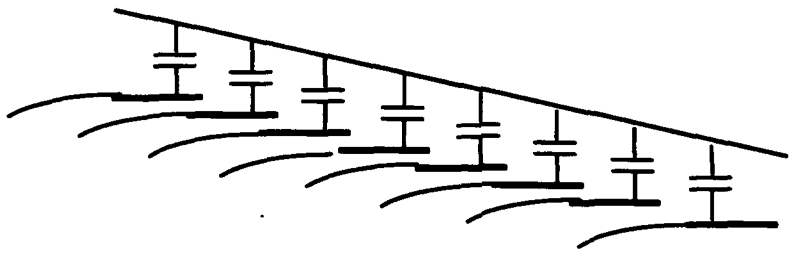
$Xc = 1/(2\pi f C)$
$C = 1/(2\pi f Xc)$
$Vc = Ic\ Xc$
$C = Ic/(2\pi f Vc)$




Solve for C using circuit model:

| | |
|---|---|
| Loop current is meter voltage /resistance | $Ic = 4.4 / 1{,}000{,}000$<br>$= 4.4$ microamps |
| Capacitor voltage is applied - measured | $Vc = 132 - 4.4$<br>$= 127.6$ volts |
| Capacitance is calculated, | $C = 4.4 \times 10^{-6} / (6.28\ 60\ 127.6)$<br>$C = 915$ picofarads |
| and distributed over the 8 conductors. | $C = 915/8 = 114.4$ pF |
| Each conductor is three meters long. | $\underline{C = 38.125\ pF / m}$ |

Eight 2.75 volt wire lengths acting as parallel capacitors of 115 pF each.



3 meter length of coil wire next to test cable has:
16.6 mH inductance and a voltage of 2.75 volts

Figure 2.4 - Capacitior Circuit Model

## PART 3
## MATERIAL AND EQUIPMENT

To simulate the environment of a power cable bank it is necessary to create large alternating currents over relatively long distances. Standard electromagnetic compatibility laboratory equipment is listed in Table II and adjusted accordingly and applied.

Table II - Test Equipment

| Equipment / Material | Manufacturer | Part Number |
|---|---|---|
| | | |
| Signal Analyzer | Hewlett-Packard | HP 3561 |
| 6' Helmholtz coil | EMCO | 7601 |
| 5" Loop Antenna | EMCO | 7604 |
| Current Probe | Pearson | 110 |
| 3 Meter Wire Sample | - | - |
| Resistor | - | - |

### Electromagnetic Field Generation with a Helmholtz Coil

A Helmholtz coil is two coils connected electrically in series and positioned so that the resultant field is same-valued over a large volume. However, the strongest fields are located at zero separation from the coil wires and they are limited by the inductance of the coils. Also, one coil can be shorted and an increase in field results on the remaining coil. The six foot coil chosen for the project has an impedance of 100 millihenries and is current limited to 20 amperes.

The coil current is measured using a 10 ampere per volt output current probe and coil electromagnetic field is measured using a calibrated 5 inch loop antenna.

### Voltage Measurements with a Fast Fourier Transform Analyzer.

The Hewlett-Packard Dynamic Signal Analyzer is ideal for this measurement because its input sensitivity automatically adjusts from 1 microvolt to 42 volts. It also has high input impedance and an adjustable frequency resolution. It displays a 60 hertz voltage and harmonics over a 500 hertz frequency range with a resolution of less than 5 hertz and an accuracy of less than 1 decibel. The current probe and the loop antenna outputs and the test wire voltages are all measured using this analyzer.

## Wire Termination Impedance

The test wire termination voltages are measured under a varying impedance. Resistors values are: 39, 1000, 10k, 150k, 1M ohm and the analyzer input is 1M ohm.

# PART 4
# MEASUREMENT PROCEDURE

## Test Setup

In order to create the high fields indicated by the calculations it is necessary to modify the Helmholtz coil and perform the testing as shown in Figure 4. The test wire is laid directly on a single coil and the other coil is shorted. The current in the coil and the field from the loop antenna are measured to calibrate the setup. Then the open circuit test wire voltages are measured at select field strengths. Finally, the wire is loaded with varying resistors and the termination voltage is measured at the select field strengths.

## Safety

Recent studies (Reference 7) have indicated health concerns over excessive exposure to low frequency magnetic flux densities. By using a single coil and by placing the test sample directly on the radiator, maximum exposure to the wire could be applied with a minimum unwanted field. Also, since field strengths decay rapidly with distance, all measurement and control equipment was placed safely away from the coil.

## Calibration

The current probe is placed on a single wire connecting to the coil but well out of the coil field. Monitoring it ensures that the same current is drawn to create the same field at each impedance. The 5 inch loop antenna has a transfer impedance of .01885 volts per gauss. It is taped into position directly on the coil to obtain uniform readings. Calibration data are collected in Table III.

## Termination Ranges

An effort was made to make the resistance values complete and realistic without compiling redundant information. The open circuit provides voltage induction and the short circuit provides almost complete rejection.

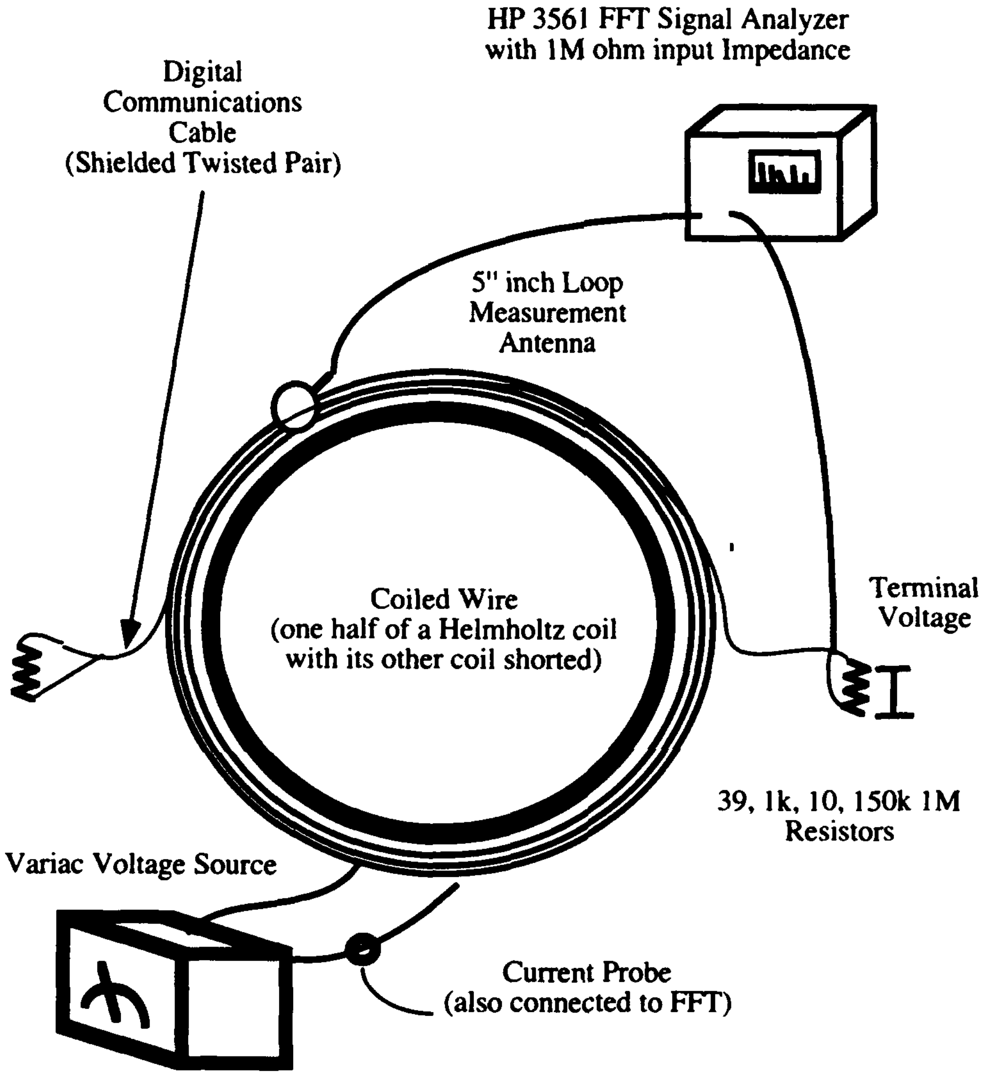
## Field Strengths

Flux density is limited to about 17 gauss by the inductance of the coils; it is possible to increase current using a shunt capacitor, but health and coil wire damage concerns discouraged that procedure.

Table III - Calibration of Coil Current and Flux Density

| Current Probe Output | | | 5" Electromagnetic Field Loop Output | | |
|---|---|---|---|---|---|
| (dBV) | (volts) | (amps) | (dBV) | (volts) | (gauss) |
| -3.0 | 0.70 | 7.0 | -10.0 | 0.32 | 16.7 |
| -5.0 | 0.56 | 5.6 | -12.0 | 0.25 | 13.5 |
| -6.0 | 0.50 | 5.0 | -13.0 | 0.22 | 11.8 |
| -12.0 | 0.25 | 2.5 | -20.0 | 0.10 | 5.3 |
| -20.0 | 0.10 | 1.0 | -28.0 | 0.04 | 2.1 |
| -50.0 | 0.003 | 0.03 | -67.0 | 0.001 | 0.4 |

Data have been taken at sufficient data points to build a family of curves that can provide extrapolation for higher values. Seventeen gauss and 2.75 volt per meter maximums are sufficient to verify the theory and calculations.




The test setup is designed to simulate a twisted wire pair in the prescence of numerous current carrying cables. The maximum field is limited by the inductance of the coil. Field strength is measured with the calibrated 5" probe and coil current is montored with a current probe. Voltage readings are taken at the resistors.

Figure 4.1 - Test Setup

# PART 5
# RESULTS

Twisted Pair Wire Voltages in Varied Impedance and Field

The data for matched and unmatched one megaohm inputs are in Table IV:

Table IV - High Impedance Wire Terminal Voltages

| Coil Voltage (volts) | Open Circuit (dBV) | Open Circuit (volts) | Balanced 1 MΩ (dBV) | Balanced 1 MΩ (volts) | Unbalanced 1 MΩ/.5 MΩ (dBV) | Unbalanced 1 MΩ/.5 MΩ (volts) |
|---|---|---|---|---|---|---|
| 132.0 | 12.7 | 4.4 | 7.1 | 2.2 | 3.5 | 1.50 |
| 105.5 | 7.0 | 2.2 | 1.1 | 1.1 | -2.0 | 0.80 |
| 94.3 | 5.1 | 1.8 | -0.1 | 1.0 | -4.4 | 0.63 |
| 47.1 | 0.6 | 1.0 | -5.0 | 0.53 | -9.0 | 0.35 |
| 18.9 | -9.1 | 0.35 | -14.8 | 0.18 | -18.5 | 0.12 |
| 0.5 | -40.0 | 0.01 | - | ~0 | - | ~0 |

and the data for matched low impedance termination are in Table V.

Table V - Low Impedance Wire Terminal Voltages

| Coil Voltage (volts) | 150kΩ/150kΩ (dBV) | 150kΩ/150kΩ (milli-volts) | 10kΩ/10kΩ (dBV) | 10kΩ/10kΩ (milli-volts) | 1kΩ/1kΩ (dBV) | 1kΩ/1kΩ (milli-volts) | 39Ω/39Ω (dBV) | 39Ω/39Ω (micro-volts) |
|---|---|---|---|---|---|---|---|---|
| 132.0 | -9.1 | 350 | -32.2 | 25.1 | -52.0 | 2.50 | -72.2 | 251 |
| 105.5 | -15.8 | 170 | -38.1 | 12.5 | -58.1 | 1.25 | -80.1 | 100 |
| 94.3 | -16.1 | 150 | -39.1 | 11.2 | -59.9 | 1.00 | -81.5 | 89 |
| 47.1 | -21.8 | 79.4 | -44.9 | 5.60 | -65.5 | 0.56 | -86.5 | 50 |
| 18.9 | -31.3 | 28.2 | -54.0 | 1.80 | -75.0 | 0.17 | -96.0 | 15 |

The voltage data are graphed versus coil current for constant impedance in Figure 5.1. Patterns in performance are apparent and the high impedance data are linearly extrapolated over a logarithmic range in Figure 5.2. Figure 5.3 is the same extrapolation for low impedance data. Figure 5.4 shows the regular decay of voltage with decreasing termination impedance under a constant field. Figure 5.5 through 5.7 show the results for voltage applied.

It is noted that the wire pair open circuit voltage data correspond to the calculations (Figure 5.8).

An interesting result is obtained by comparing the data for a twisted pair voltage in the earth's ambient field (zero applied field - Figure 5.9 ) with Figure 5.10, the data for voltage between the wire and shield immersed in a severe field. The wire and shield combination rejects voltage extremely well. If shields are available they should be connected to attenuate steady state electric fields, but low frequency magnetic field effects (ground loops) may occur.

## Estimating Circuit Immunity

The test results in Figure 5.2 establish an empirical transfer function between radiated electromagnetic source and voltage at wire terminals at a constant high impedance.

Empirical relationships are developed for the low frequency cases in Figure 5.3.

## Circuitry Selection

Figure 5.4 can be used for circuitry selection by bounding input impedance and sensitivity when subject to a known field strength. It also shows that low impedance is generally preferable for unshielded wire termination in a severe low frequency environment.

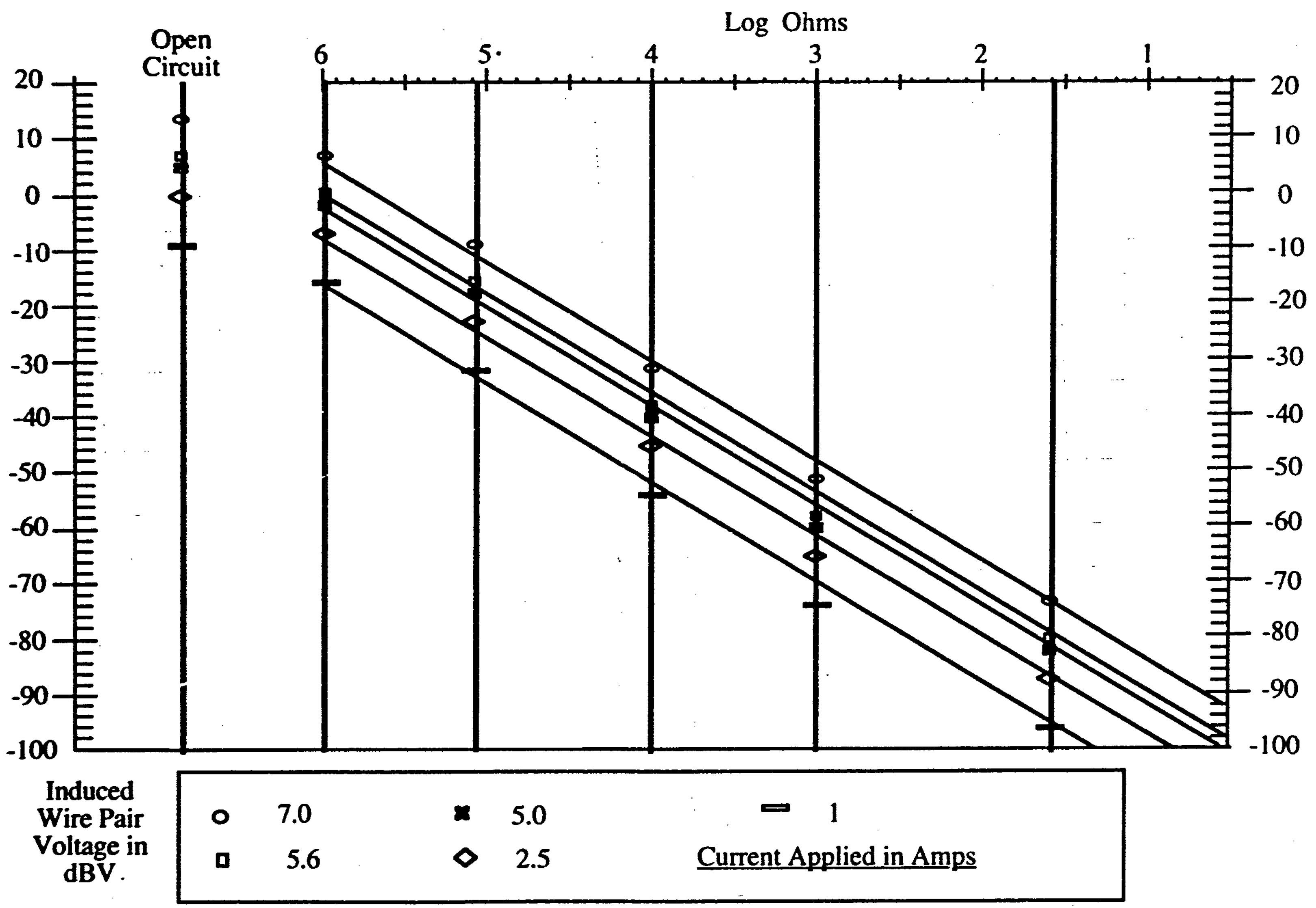



Figure 5.1 -Voltage Induced in dB versus Log Ohms

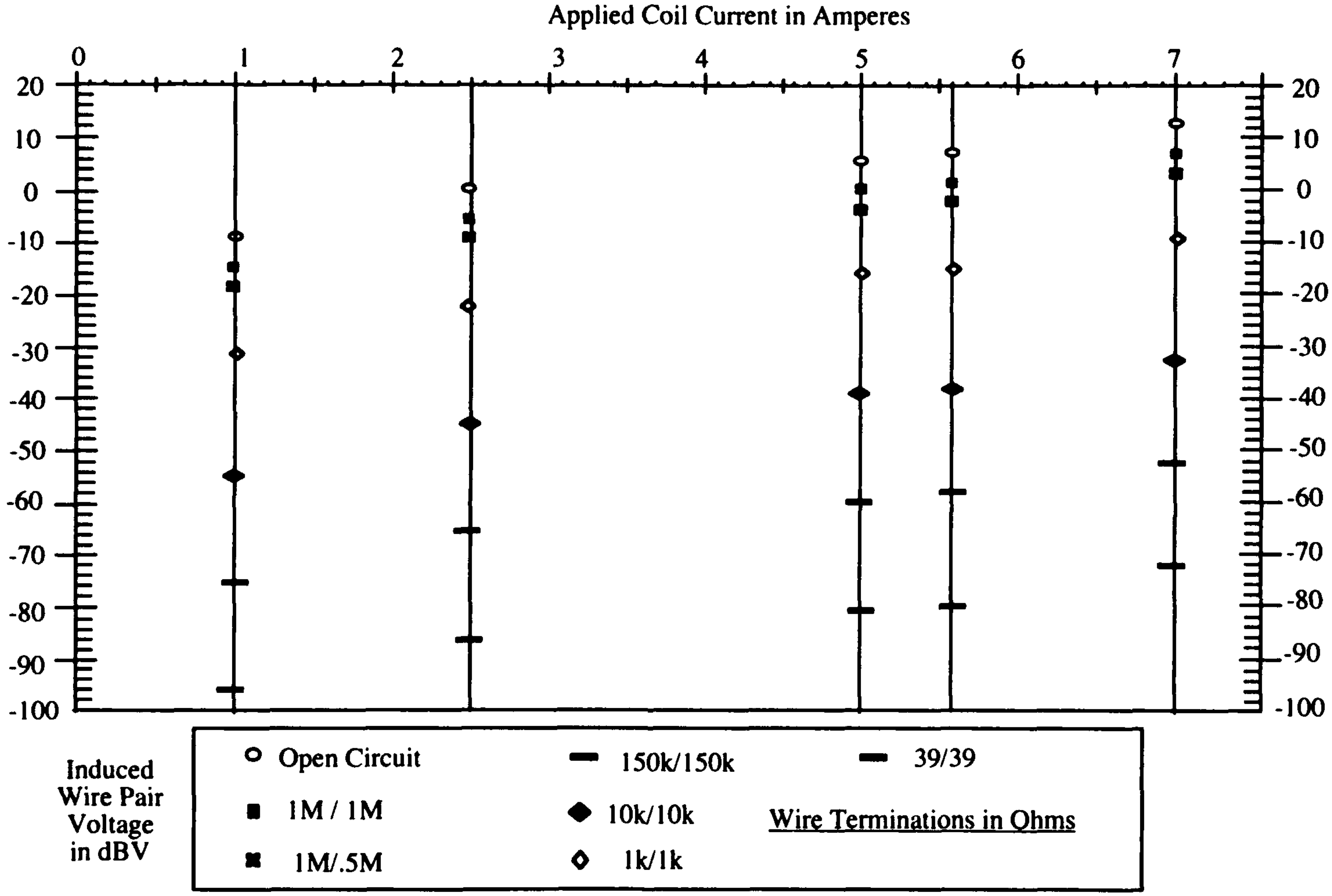
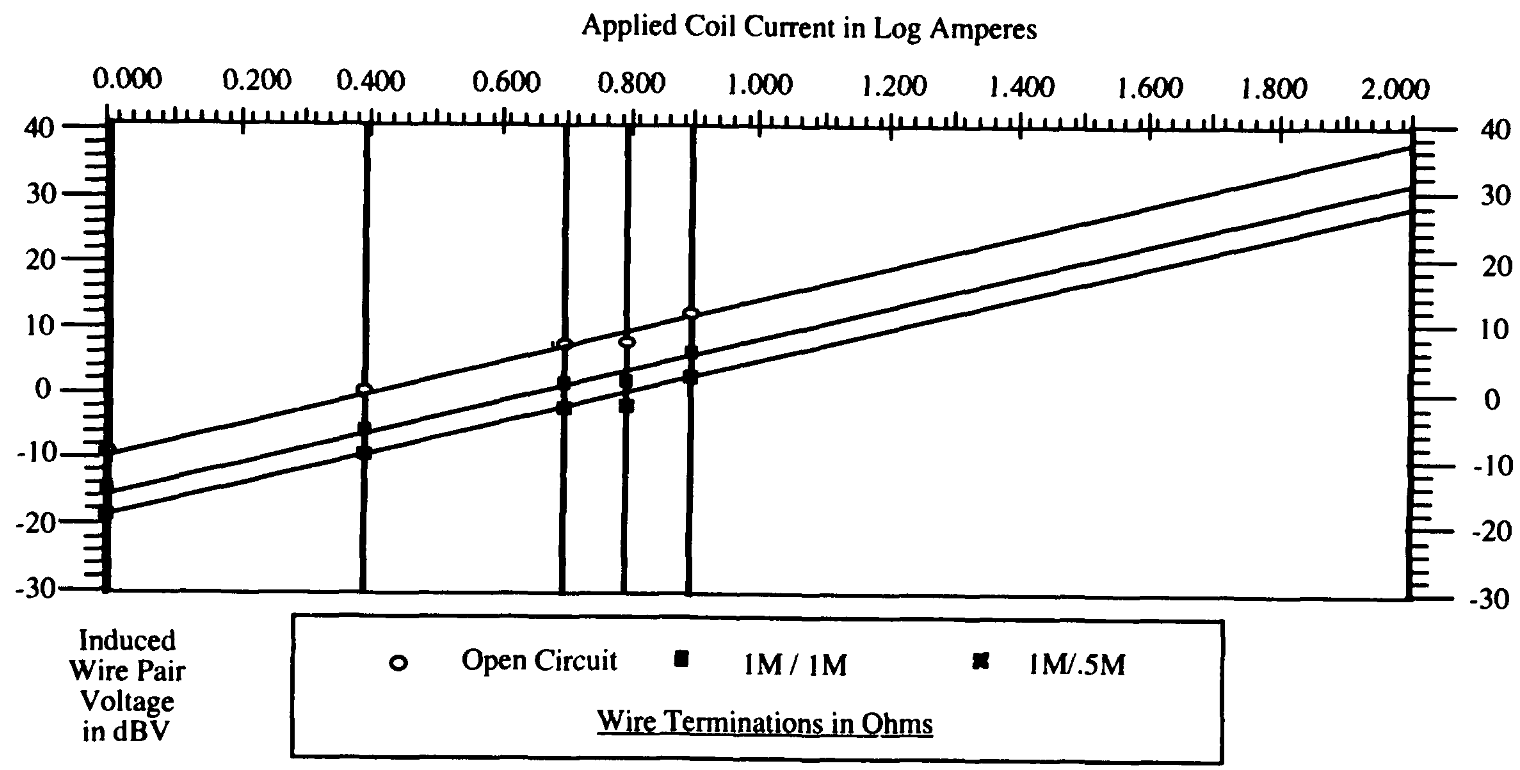


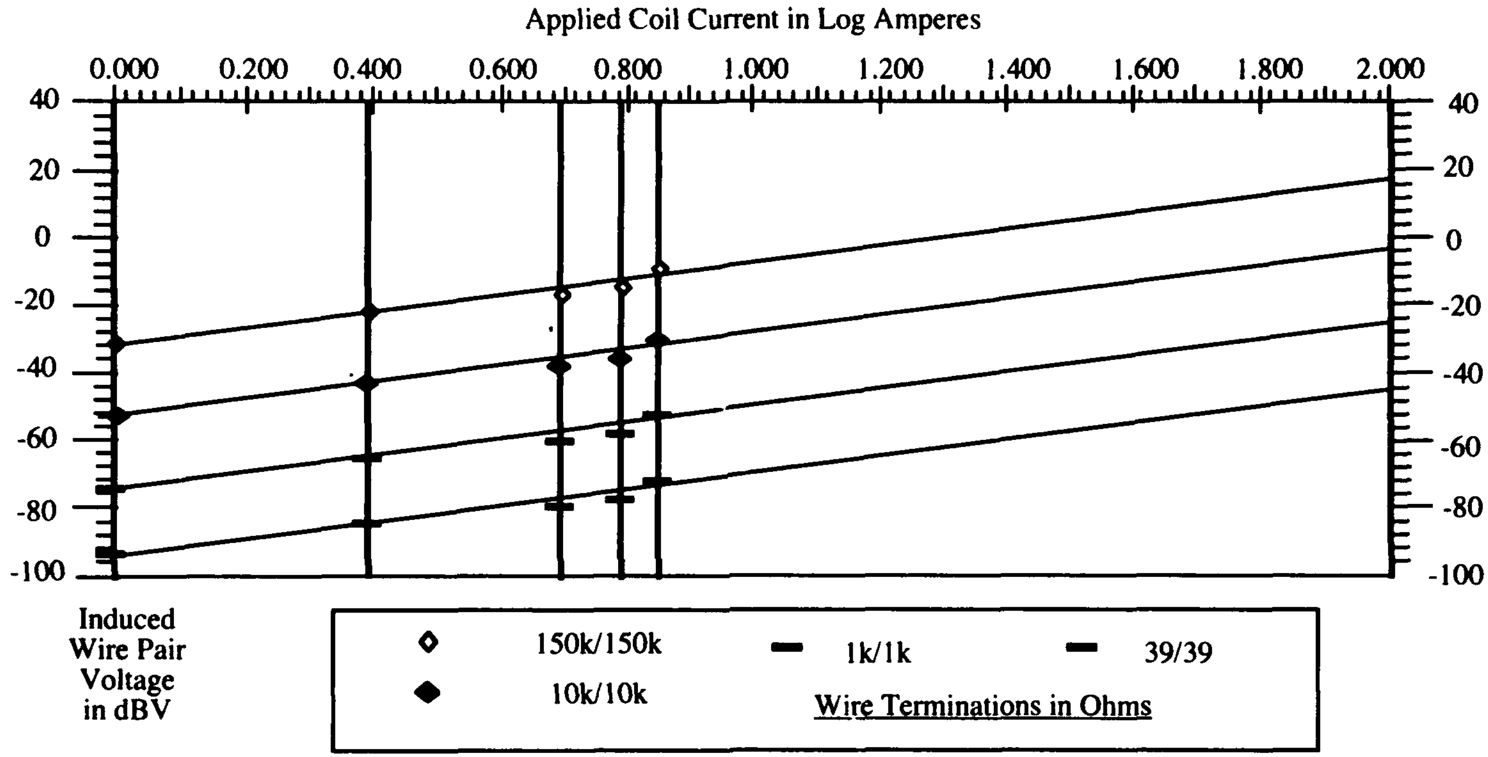

Figure 5.2 - Voltage Induced in dB vs. Coil Current




A linear extrapolation correlating voltage and neighboring current flow for an 18 gauge twisted wire pair gives the following empirically derived equations:

Open circuit dBV = -10 + 24 * log (amps)
Balanced 1M Ohm terminations dBV = -15 + 24 * log (amps)
Unbalanced 1M/.5M Ohm terminations dBV = -19 + 24 * log (amps)

Figure 5.3 - Voltage Induced in dB versus Log Coil Current




A linear extrapolation correlating voltage and flux density for an 18 gauge twisted wire pair gives the following empirically derived equations:

Balanced 150k ohm terminations: dBV = -30 + 24 * log (amps)
Balanced 10k ohmterminations: dBV = -50 + 24 * log (amps)
Balanced 1k ohm terminations: dBV = -75 + 24 * log (amps)
Balanced 39 ohm terminations: dBV = -96 + 24 * log (amps)

Figure 5.4 - Voltage Induced in dB versus Log Coil Current

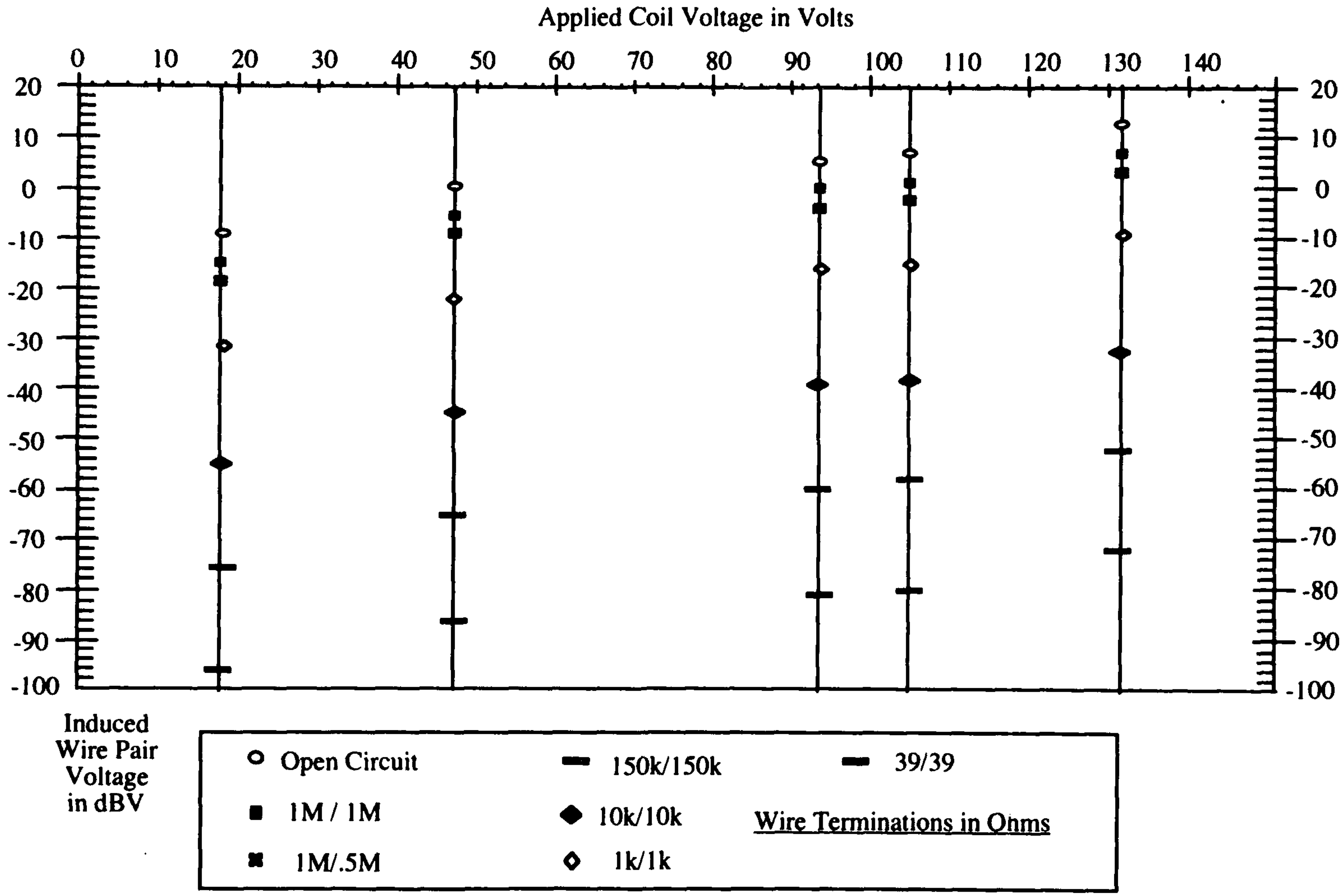
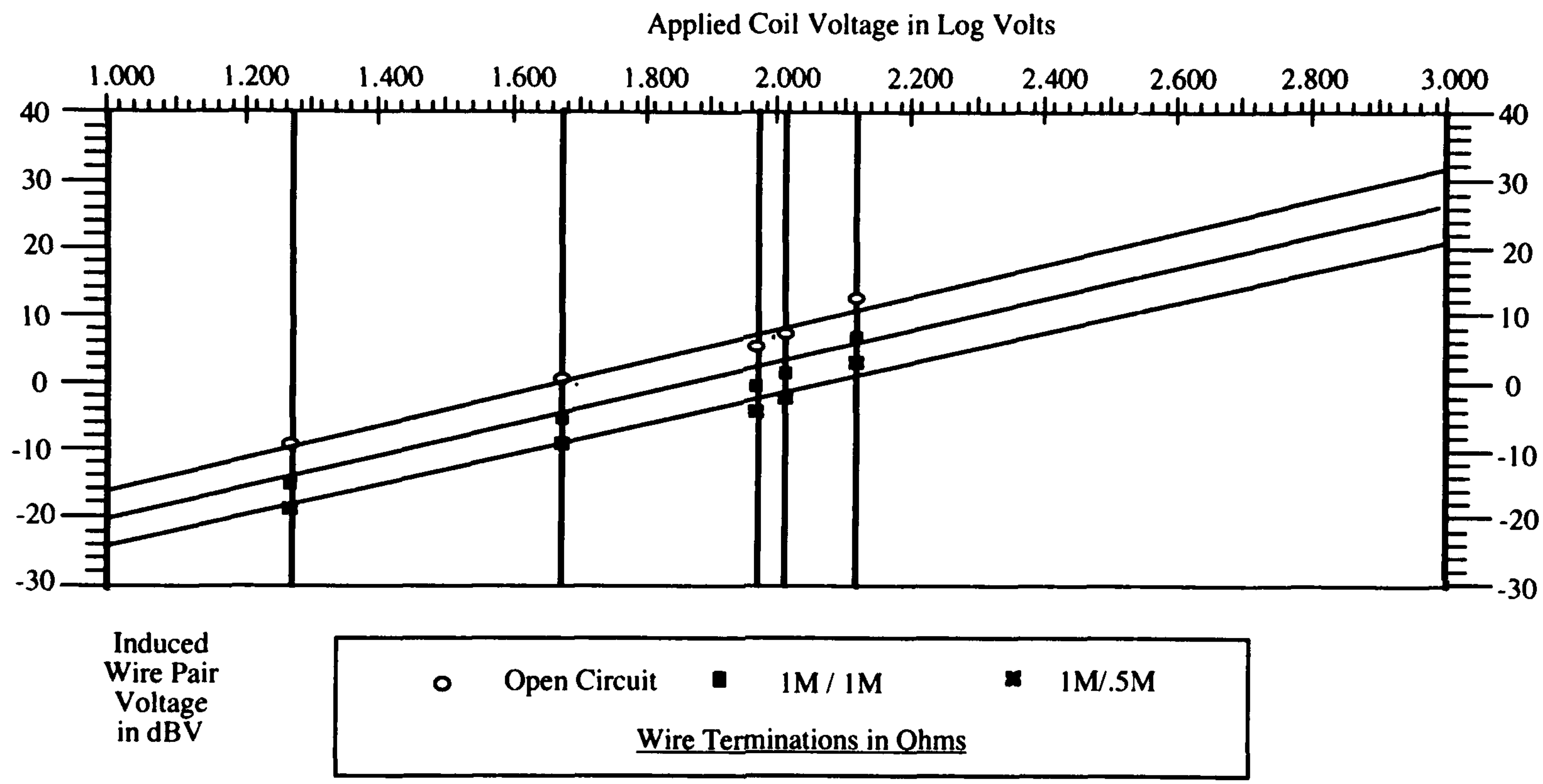


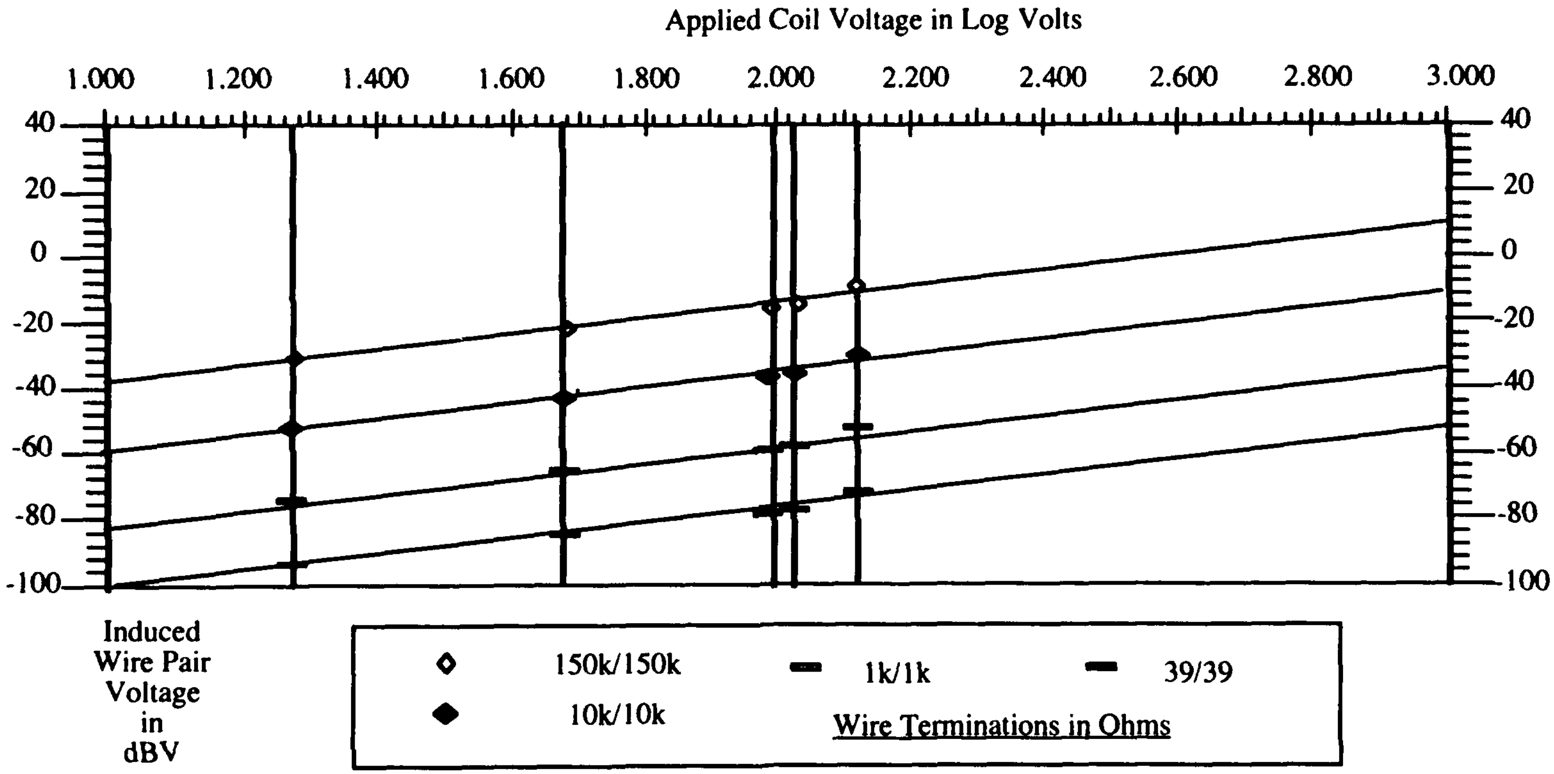

Figure 5.5 - Wire Voltage Induced in dB vs. Coil Voltage




A linear extrapolation correlating induced voltage and neighboring voltage for an 18 gauge twisted wire pair gives the following empirically derived equations:

Open circuit dBV = -16 + 24 * log (volts)
Balanced 1M Ohm terminations dBV = -21 + 24 * log (volts)
Unbalanced 1M/.5M Ohm terminations dBV = -24 + 24 * log (volts)

Figure 5.6 - Voltage Induced in dB versus Log Coil Voltage




A linear extrapolation correlating voltage induced and neighboring voltage for an 18 gauge twisted wire pair gives the following empirically derived equations:

Balanced 150k ohm terminations: dBV = -39 + 24 * log (volts)
Balanced 10k ohm terminations: dBV = -61 + 24 * log (volts)
Balanced 1k ohm terminations: dBV = -83 + 24 * log (volts)
Balanced 39 ohm terminations: dBV = -105 + 24 * log (volts)

Figure 5.7 - Voltage Induced in dB versus Log Coil Voltage

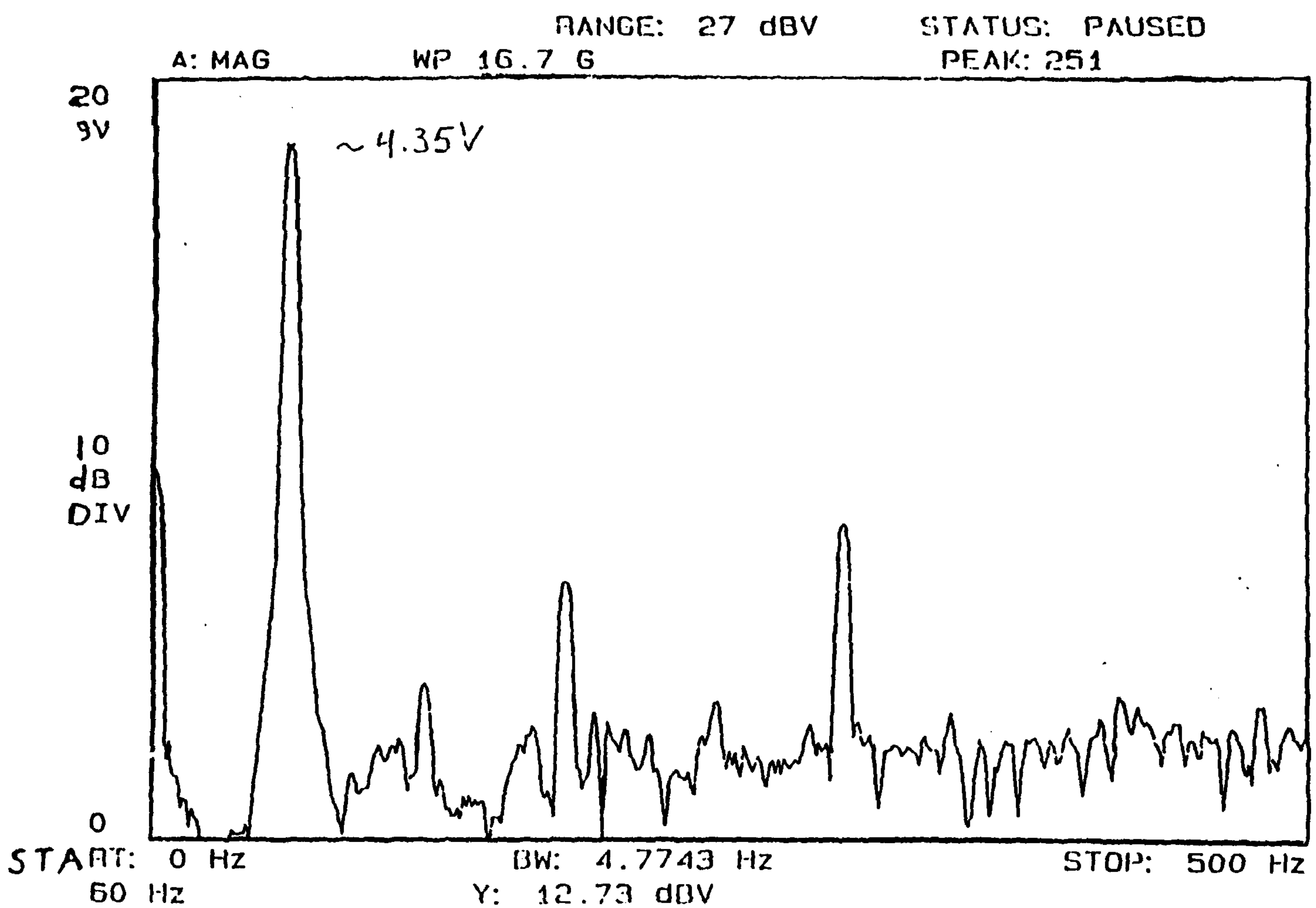



Figure 5.8 - Open Circuit Wire Pair Voltage - 132 Volts Applied

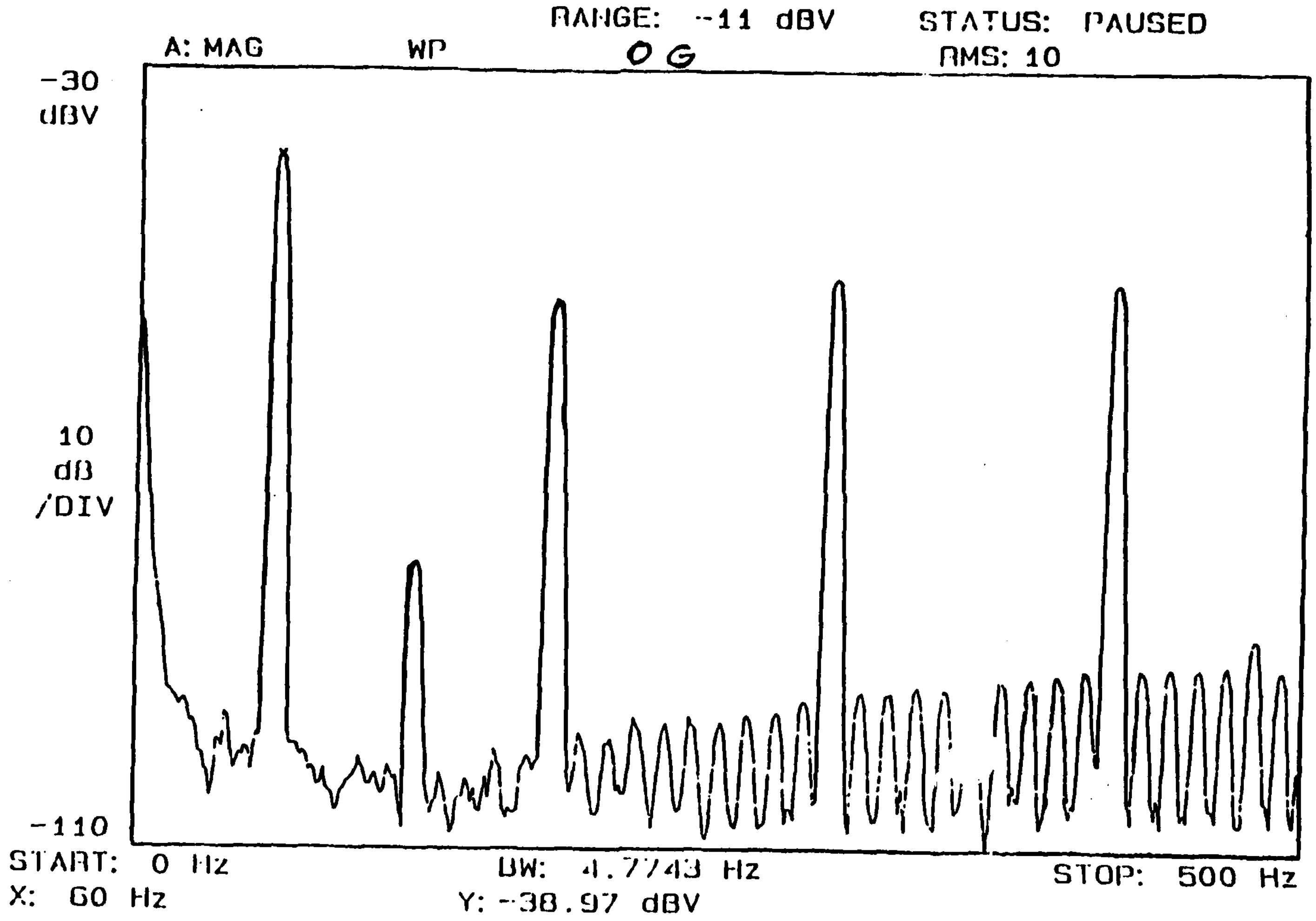



Figure 5.9 - Open Circuit Wire Pair Voltage - Zero Voltage Applied

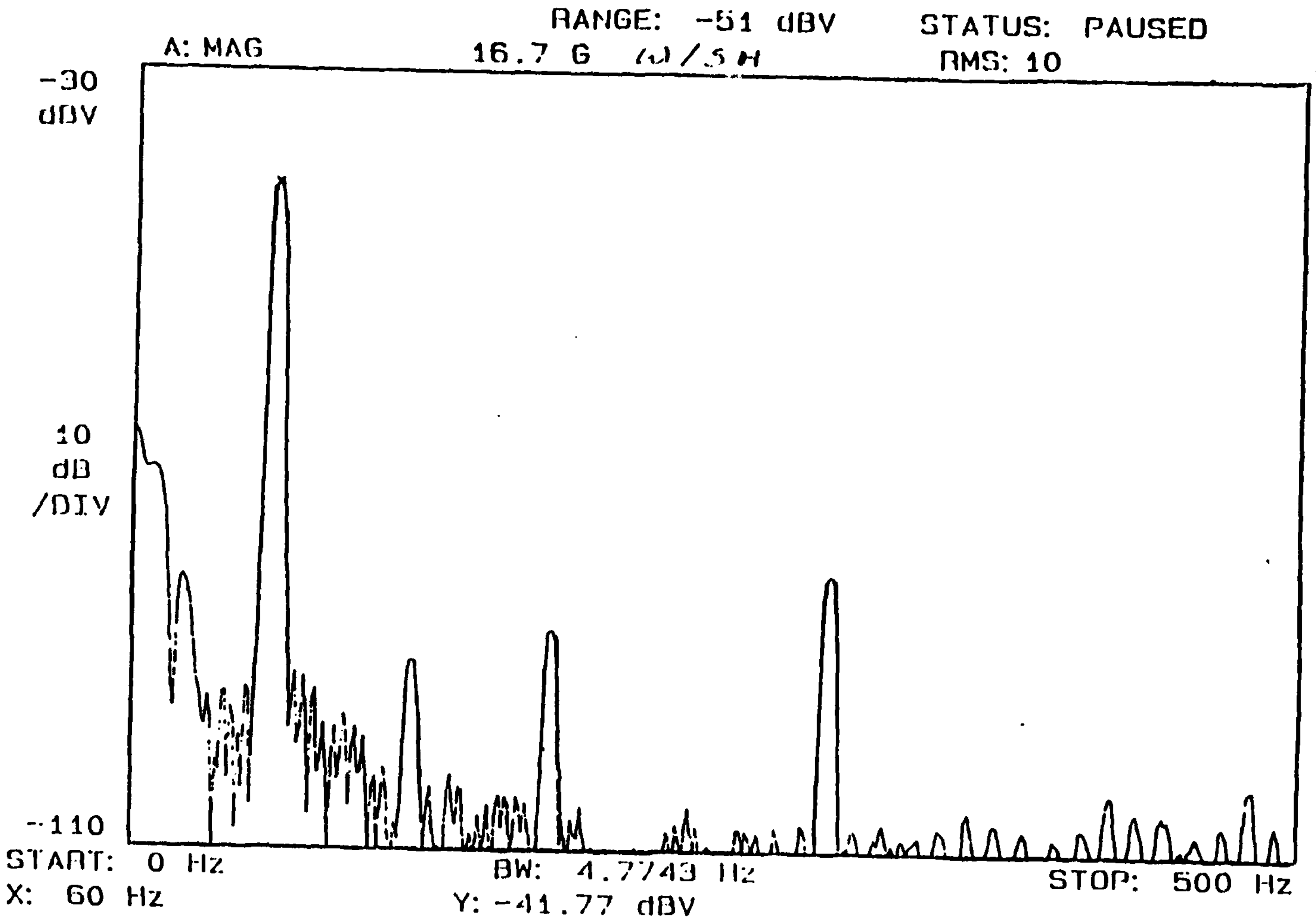



Figure 5.10 - Open Circuit Wire/Shield Voltage - 132 Volts Applied

## PART 6
## DISCUSSION AND CONCLUSION

The data show that high noise voltage can be expected on unshielded twisted pairs when field strength and termination impedance are high. Two physically close wires have a capacitance per foot between them and the inductance per meter of a radiating wire creates a potential difference on it. Lengths of several meters create sufficient electric fields to couple large noise voltages onto a susceptor wire.

However, the small effective loop area of twisted pair wire results in a small voltage induced by even the strongest of magnetic fields. Electric fields are the predominate effect in this circumstance.

Circuits normally have high impedance for noise rejection; in this case lower impedance provide better performance. Possibilities of using resistors as filters on unshielded twisted pairs are available as long as current draw does not cause problems.

The uniformly twisted type wire and shield combination provide excellent performance. In cases where high frequency common mode noise is not an issue, this "quasi-coaxial cable" combined with proper shield termination may be an ideal solution.

For the unshielded example cited, the only circuitry that will provide enough electromagnetic field immunity and not create other problems is the balanced receiver collector output driver combination.

The curves created should be an effective tool to anyone encountering noisy digital circuitry installations. The extrapolation should be very accurate in the neighborhood of the measured voltages and a reasonable estimate elsewhere.

To design a circuit immune to a severe electromagnetic field environment, the input impedance should be kept as low as possible and receiver sensitivity voltage, including hysteresis, should be kept as high as possible. If the field can be described uniquely, then circuit tolerances can be selected to ensure non-disrupted communications.

The electric field data collected is also dependent on the voltage drop over the length of the sample; the length and voltage in this case is dictated by the radiating coil size.

The intent of this project was to ensure that the length used was as long as feasible to best represent real conditions. However, longer lengths of wire will likely have larger voltage drops and consequently produce higher voltages.

Transient conditions are also likely in a severe electromagnetic environment, and complete 360 degree grounding of cable shields will provide immunity for a system. For a shield to wire connection or for unshielded pairs, low pass filters should be used on communication wiring.

It is also likely that adaptive filtering techniques will be useful in high noise situations.

## PART 7
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